# A methodology to estimate uncertainty for emission projections through sensitivity analysis

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*Air pollution abatement policies must be based on quantitative information on current and future emissions of pollutants. As emission projections uncertainties are inevitable and traditional statistical treatments of uncertainty are highly time/resources consuming, a simplified methodology for nonstatistical uncertainty estimation based on sensitivity analysis is presented in this work. The methodology was applied to the "with measures" scenario for Spain, concretely over the 12 highest emitting sectors regarding greenhouse gas and air pollutants emissions. Examples of methodology application for two important sectors (power plants, and agriculture and livestock) are shown and explained in depth. Uncertainty bands were obtained up to 2020 by modifying the driving factors of the 12 selected sectors and the methodology was tested against a recomputed emission trend in a low economic-growth perspective and official figures for 2010, showing a very good performance.*

*Implications:* A solid understanding and quantification of uncertainties related to atmospheric emission inventories and projections provide useful information for policy negotiations. However, as many of those uncertainties are irreducible, there is an interest on how they could be managed in order to derive robust policy conclusions. Taking this into account, a method developed to use sensitivity analysis as a source of information to derive nonstatistical uncertainty bands for emission projections is presented and applied to Spain. This method simplifies uncertainty assessment and allows other countries to take advantage of their sensitivity analyses.

## Introduction

An increased awareness of the importance of evaluating uncertainty (Engau and Hoffmann, 2009; Maxim and van der Sluijs, 2011; Pouliot et al., 2012) is arising in environmental science for policy. An important issue for environmental policy is the development of atmospheric emission inventories and projections not only to monitor progress toward compliance with legislation but also to evaluate the effect of abatement strategies to reduce future emissions (Samaras et al., 1999). Although both emissions and projections should be calculated following widely accepted methodologies (European Environment Agency [EEA], 2013; Intergovernmental Panel on Climate Change [IPCC], 2006), their uncertainties are high and some of them are unavoidable (IPCC, 2000). The main sources of uncertainty are as follows: data quality, lack of consistency between related activities, different interpretations of pollutant categories, definitions, and so on. Therefore, emission inventories and projections should include uncertainty estimations to aid the decision-making process (Miller et al., 2012; Raadgever et al., 2011; Schultz, 2008). However, in this context, a new notion of uncertainty is used that includes not only epistemic uncertainty, but also ontological uncertainty (unpredictability) and ambiguity (the existence of multiple framings) (Raadgever et al., 2011). Therefore, uncertainty is understood as a consequence of variabilities, data entry, and other errors and assumptions in emission measurements, activity data, and emission models (Miller et al., 2012). Consequently, quantification is very complex and difficult to isolate (Miller et al., 2012).

When precise results are required, it is useful to express uncertainty quantitatively and systematically in the form of well-developed confidence intervals (e.g., Lumbreras et al., 2009). However, quantitative estimation and treatment of uncertainties might be highly time-consuming and far from trivial due to the complexity of emission projection systems (van Sluijs, 1996). Different emission inventory and emission projection studies have considered quantitative analyses of uncertainty (Rypdal, 2002; Schöpp et al., 2005; Webster et al., 2002) but in many cases are applied to a specific sector or in a fragmented way (Frey and Zheng, 2002; Heath and James, 2000; Kioutsioukis et al., 2004; Panis et al., 2004; Jong et al., 2007; Sangil et al., 2014; Singh et al., 2008). Moreover, a peer review team that analyzed a European Integrated Assessment Model (Commission of the European Communities [CEC], 2004) concluded that such traditional statistical analyses, although important, may be of limited value in a policy context if not considered in relation to other uncertainties, such as uncertainties due to biases in model formulation, lack of scientific understanding, or the inability to predict future behavior.

Taking into account the already-mentioned disadvantages of quantitative approaches, a group of experts recommended simple and qualitative methods, useful to derive robust policy conclusions (EC4MACS, 2010). Following this recommendation, this paper presents a method based on sensitivity analyses (SA), which are the studies of the variation in the outputs of a model based on the modification of certain input parameters. The main purpose of this kind of analysis is to assess how the optimal solution is affected by changes in initial conditions. Additional information about which are the main variables affecting model outputs and the extent they influence the results can be obtained.

Leneman et al. (1998) conducted SA to identify the effect of uncertainties on ammonia emissions with respect to emission factors and the implementation of emission abatement techniques in the Netherlands. Gumerman et al. (2001) presented a range of policy scenarios composed of different subsets of policy interventions and different energy prices in the United States in order to provide insight into the costs and carbon-reduction impacts of a carbon permit trading system, demand-side efficiency programs, and supply-side policies. Arogo et al. (2010) carried out SA to determine the input parameters and their interactions that contribute most to the outcomes of an ammonia emission modeling system. Examples of the use of SA are found in national communications by the parties to the United Nations Framework Convention on Climate Change. Concretely, in the last version of the USA Climate Action Report (Government of the United States of America [GUSA], 2014), the U.S. Environmental Protection Agency developed a set of scenarios of changing retail energy prices, economic growth paths, technology developments, composition of economic activity, and government policies leading to a range of possible outcomes. In the same way, two sensitivity scenarios were designed by the Swedish Ministry of the Environment based on alternative assumptions on fossil fuel prices, emissions of fluorinated greenhouse gases in the industrial processes sector, trends in gross domestic product (GDP), and production of the agricultural sector in the Sweden's Sixth National Communication on Climate Change (Swedish Ministry of the Environment [SME], 2014).

Additionally, there is a need to incorporate some balanced and rational mechanism of flexibility in decision making to account for unforeseen changes (Kelly et al., 2010), so SA can also be useful in the process of emission target determination for future environmental/climate policies. For instance, in selecting a climate target, policy maker's decisions on greenhouse gas (GHG) emissions could be insufficient or excessively stringent,resulting in environmental/economic problems (Anda et al., 2009). The use of SA in the determination of the flexibility mechanisms might reduce these drawbacks.

However, these analyses have not been used to estimate the uncertainty of emission projections. This work presents a method developed to use SA as a source of information to derive non-statistical uncertainty bands for emission projections.

This approach intends to provide a holistic picture of uncertainties in practice more than trying to assess uncertainties and errors under a formal statistical framework, since these methods usually are very expensive computationally and are based on a theoretical basis and fundamentals that may not be applicable to practical emission projections methods. This methodology focuses primarily on the activity levels that can be affected by policies to a larger extent.

Although uncertainty bands appear as quantitative results, it is important to notice that these results are qualitative, according to the previous discussion. The method was applied to Spain over the most relevant sectors regarding the Kyoto Protocol (United Nations Framework Convention on Climate Change [UNFCCC], 1998; regarding GHG emissions) and National Emission Ceilings Directive (European Community [EC], 2001; setting up national emission limits for ammonia, sulfur oxides, nonmethane volatile organic compounds, and nitrogen oxides) pollutants, as well as particulate matter. This methodology simplifies uncertainty assessment and allows other countries to take advantage of their sensitivity analyses (much applied rather than uncertainty computation). Methodology application for two sectors (power plants, and agriculture and livestock) is shown and explained in depth. Results from a "with measures" (WM) scenario based on the Spain's National Atmospheric Emission Inventory 1990–2006, SNAEI 2006 (Ministry of Environment, Rural and Marine Affairs [MARM], 2008), are compared with recomputed emission trends in a low economic growth perspective based on the Spain's National Atmospheric Emission Inventory 1990–2007, SNAEI 2007 (MARM, 2009), and with the subsequent Spain's National Atmospheric Emission Inventory 1990–2010, SNAEI 2010 (MARM, 2012) providing a good test of the method.

## Methodology

The uncertainty from sensitivity analysis (UFSA) method was developed to obtain uncertainty bands from a particular emission projection scenario. Thus, it is possible to estimate the future "possible" deviations from the emission projections estimated. The calculations can be carried out for a given year or throughout the projected period. The general methodology consists of five steps:

(1) Analysis of the key factors driving emissions of each emitting activity. Each activity is studied to extract those factors determining the activity behavior that could be changed to derive the sensitivity analysis, considering that if the emissions come from only one source, the only option for reducing emissions is a reduction in activity level.
(2) Analysis of the emissions influence of each factor. As a first analysis, these factors are modified in a given extent to get a glimpse of the induced changes in sector emissions.
(3) Definition of the most probable range of variation for each factor. Intervals are defined based on statistical analyses (e.g., standard deviation of values from past years, which

**Table 1.** Sectors involved in UFSA calculations (values regarding KP, NECD pollutants and particulate are in percent of Spanish emissions according to the scope and according to the SNAEI 1990–2006)

| Sector | SOx | NOx | NMVOC | $CH_4$ | $CO_2$ | $N_2O$ | $NH_3$ | $SF_6$ | HFC | PFC | $PM_{2.5}$ | $PM_{10}$ | TPM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Power plants | 70.9 | 20.2 | 0.8 | 0.3 | 28.0 | 1.8 | 0.0 | 0.0 | 0.0 | 0.0 | 7.1 | 10.4 | 10.2 |
| Residential combustion plants <50 MW | 1.1 | 1.3 | 4.0 | 1.6 | 5.0 | 0.7 | 0.0 | 0.0 | 0.0 | 0.0 | 16.3 | 13.4 | 10.1 |
| Combustion in manufacturing industry plants | 8.2 | 15.6 | 2.6 | 0.5 | 15.2 | 1.6 | 0.0 | 0.0 | 0.0 | 0.0 | 6.0 | 6.2 | 6.8 |
| Aluminum production | 0.3 | 0.1 | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 55.5 | 0.4 | 0.7 | 0.6 |
| Cement production | 1.5 | 3.5 | 0.2 | 0.0 | 7.9 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.8 | 0.6 |
| Paint and solvent application | 0.0 | 0.0 | 37.3 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Refrigeration and air conditioning equipments using halocarbons | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 76.1 | 43.0 | 0.0 | 0.0 | 0.0 |
| Electrical equipments (except electronic components manufacturing) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 100.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Road transport | 0.2 | 32.9 | 17.5 | 0.5 | 26.5 | 9.0 | 1.9 | 0.0 | 0.0 | 0.0 | 24.6 | 21.8 | 18.0 |
| Rail transport | 0.0 | 0.3 | 0.0 | 0.0 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.2 | 0.1 |
| Waste management | 0.0 | 0.1 | 0.0 | 19.3 | 0.2 | 0.2 | 1.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Agriculture and livestock | 1.0 | 9.0 | 5.8 | 63.2 | 2.1 | 80.1 | 96.2 | 0.0 | 0.0 | 0.0 | 23.5 | 26.8 | 37.5 |
| Total (2006) | 83.4 | 83.0 | 68.3 | 85.4 | 85.4 | 93.9 | 99.7 | 100.0 | 76.1 | 98.5 | 78.7 | 80.1 | 84.0 |
| Average contribution (2000–2006) | 83.7 | 82.5 | 75.2 | 81.6 | 85.5 | 93.8 | 98.9 | 100.0 | 66.3 | 77.9 | 80.1 | 81.0 | 84.7 |

*Notes*: $SO_x$, sulfur oxides ($SO_2$ + $SO_3$), as mass of $SO_2$; $NO_x$, nitrogen oxides (NO + $NO_2$), as mass of $NO_2$; NMVOC, nonmethane volatile organic compounds; $SF_6$, sulfur hexafluoride; HFC, hydrofluorocarbons; PFC, perfluorocarbons; $PM_{2.5}$, particles with aerodynamic diameter less than 2.5 μm; $PM_{10}$, particles with aerodynamic diameter less than 10 μm; TPM, total particulate matter.

could be a caveat in terms of error accuracy but incorporates uncertainty linked to future estimation methods), information provided by experts from different activity sectors, and expected evolution of drivers in the future (e.g., GDP, population).

(4) Computation of the variation effect on national total emissions. At this stage, each activity emission is recalculated modifying factor values within the already-mentioned ranges.
(5) Determination of nonstatistical uncertainty bands. All previous calculations are added in a consistent way.

This method should be ideally applied over all the emitting activities. However, this procedure might be highly time-consuming. Due to the fact that simplicity is one of the main advantages of SA compared to quantitative estimation of uncertainties, it could be advisable to reduce the analysis to the most relevant (emitter) sectors. Thus, the UFSA might be carried out in a more efficient way without affecting significantly the quality of the results obtained. Despite this, it should be noted that substantial expertise is required to apply this methodology properly. The key factors driving emissions and their most probable ranges of variation must be appropriately identified/defined and the potential relations between any of these key factors and different emitting activities must be fully considered.

## Methodology application

In this work, the application of the methodology to the so-called "with measures" scenario (WM, see the "Scenarios Analyzed" section) for Spain is presented. Concretely, the UFSA method was applied to 2010. This year was selected as the central year of the 5-year Kyoto Protocol (KP) commitment and as the deadline for compliance with the National Emission Ceilings Directive (NECD). The work was not carried out over all the emitting activities of Spain but over the 12 activity sectors that produced most of the national emissions according to SNAEI 2006 (Table 1). In this case, the methodology used consisted of six steps (adding the previous selection of the most relevant emitters):

(1) Selection of the 12 highest emitting sectors. The selected sectors should cover most of emissions (ideally 75% or more) for all the relevant pollutants. A compromise must be found between maximum emissions covered and minimum number of sectors.
(2) Analysis of the key factors driving emissions of each selected sector.
(3) Analysis of the influence of each factor on emissions at sectoral level. For this purpose, the value of each parameter in 2010 according to WM scenario was modified in a range of ±20%, in 5% intervals.
(4) Definition of the most probable range of variation for each factor. (In this contribution, two of the 12 selected sectors were chosen to be described in depth. The most probable ranges of variation for these two sectors, shown in Table 2, result from the analysis that follows.)
(5) Computation of the variation effect on national total emissions using factor values selected.
(6) Derivation of nonstatistical uncertainty bands on a national scale for the WM scenario.

**Table 2.** Definition of the most probable range of variation for the key factors

| Sector | Key factor | Upper limit | Lower limit |
|---|---|---|---|
| Power plants | Total fuel consumption (TFC) | +5% | –5% |
| | Natural gas consumption (NGC) | +7% | –2% |
| | Coal consumption (CC) | +5% | –5% |
| Agriculture and livestock | Field of cultures with fertilizers (FF) | +2% | –2% |
| | Inorganic fertilizer applied (IF) | +10% | –10% |
| | Dairy cattle heads | +5% | –10% |
| | Other cattle heads (OC) | +5% | –5% |
| | Fattening pigs heads (FP) | +10% | –5% |
| | Sows heads | +5% | –5% |
| | Sheep heads | +5% | –5% |
| | Laying hens heads | +5% | –5% |
| | Urea proportion of fertilization (UP) | +5% | –5% |

*Emission sectors involved.* The UFSA was applied to the 12 highest emitting sectors regarding emissions of KP, NECD pollutants, and particulate matter. GHG were estimated in the scope of KP, while $NH_3$, NMVOC, $NO_x$, and $SO_x$ and particulate matter were determined in the scope of NECD. Sectors involved and pollutants considered are shown in Table 1. These sectors contain one or more emission categories according to the Selected Nomenclature for Air Pollution (SNAP) classification (EMEP-CORINAIR, 2007). Each activity was gathered in a specific sector in a consistent way using the Consistent Emission Projection (CEP) model for Spain (Borge et al., 2005; Lumbreras et al., 2008), which considers every emission activity covered in the emission inventory.

These sectors enable the method to obtain uncertainties for Spanish sources that contribute 83% of $SO_2$ emissions, 85% of $CO_2$ emissions, 83% of $NO_x$, 99% of $NH_3$, 80% of $PM_{10}$, and 79% of $PM_{2.5}$, based upon SNAEI 2006.

*Scenarios analyzed.* The methodology was applied to the "with measures" (WM) scenario, based on SNAEI 2006 data. The WM scenario was intended to provide national emission projections in consistence with the homonymous scenario defined in the Clean Air For Europe (CAFE) program, a European program aimed to the establishment of a long-term, integrated strategy to tackle air pollution and to protect against its effects on human health and the environment. It included implemented policies and measures for reducing emissions through technology improvements and dissemination, demand-side efficiency gains, more efficient regulatory procedures, shifts to cleaner fuels, and so on (Lumbreras et al., 2008).

UFSA results from WM scenario were compared with recomputed emission trends in a low economic growth perspective (LEG scenario). Over the basis of SNAEI 2007, without methodology changes respect to the previous version (SNAEI 2006), the LEG scenario was calculated applying also the CEP model to Spain but considering new economic forecasts for 2009–2013 based on financial and economic crisis (Ministry of Economy and Finance [MEH], 2009). These forecasts provided new activity rates (electricity consumption, industrial production, mobility, etc.) that stemmed from new macroeconomic values (GDP, population, prices, etc.). Therefore, the scenario WM90-07 is just an update of scenario WM90-06 in view of recent macro-economic data (years 2007–2008) and the consequent update of the corresponding forecasts.

## Sectoral Application

This section presents examples of the application of the UFSA methodology for two of the 12 highest emitting sectors in Spain: power plants, and agriculture/livestock.

### Power plants sector

This sector groups the emissions from power plants consuming fossil fuels (Subgroup SNAP 01.01). As shown in Table 1, it is a relevant sector regarding emissions of $SO_x$, $CO_2$, $NO_x$, and particulate matter.

*Key factors.* The modified parameters in this sector were:

- Total fuel consumption (TFC).
- Natural gas consumption (NGC).
- Coal consumption (CC).

Variations in the NGC and CC were taken into account because they account for the majority of the fuel consumption in the sector. A gradual substitution of coal for natural gas was supposed by means of/as a result of the introduction of clean coal technologies, combined cycles, its relevance on $SO_x$ and $NO_x$ emissions, yield increases, and so on. While fuel switching, total consumption (TFC) was kept constant and the compliance with the National Emission Reduction Plan for Large Combustion Plants (NERP-LCP) was ensured according to Directive 2001/80/EC (2001). In parallel, TFC was modified because changes in total electricity demand and/or changes in the generation mix (depending on the extent of renewable energies and nuclear generation) might be possible. For this case, the relative contribution of each fuel to the TFC was kept constant and equal to that projected for 2010 in the WM scenario.

*Influence of key factors on sector emissions.* The effect of key factors variations over several pollutant emissions at the sectoral level is shown in Figure 1. Figure 1a reveals the significant effect of TFC variation on $CO_2$ emissions. However, its influence is lower on $SO_x$ emissions as a result of the compliance with the NERP-LCP. Although not shown here, the same trend was found for $NO_x$ and $PM_{2.5}$ emissions.

The increase of NGC was at the expense of reducing CC, resulting in an emissions decrease which is similar for every pollutant (Figure 1b). This can be explained because natural gas emission factors are lower than those of coal. Additionally, higher NGC produced an electricity generation yield improvement due to the fact that in Spain coal is consumed in conventional power plants while natural gas is used in combined-cycle power plants. Increased NGC implies a larger share of this technology and therefore a decrease in emissions for the same amount of energy produced.

In the case of CC (Figure 1c), the $SO_x$ (and $NO_x$ and $PM_{2.5}$) emissions were again conditioned by the restrictions imposed by NERP-LCP and almost unaffected. Regarding $CO_2$, the increase in CC produced higher emissions. The NERP-LCP introduced important limitations on $SO_x$, $NO_x$, and particulate matter emissions from power plants. Regarding $SO_x$ emissions, the NERP-LCP set very restrictive targets for annual emission, so that plants burning coal, and greatly exceeding that maximum emission permitted, were forced to install secondary measures for reducing $SO_x$ emissions (such as wet scrubbing systems). The high abatement efficiency of these secondary measures implied that the actual $SO_x$ emission factor of coal was considerably diminished. Consequently, a given variation in CC produced a much lesser variation in $SO_x$ emissions for the whole sector. On the contrary, there were no $CO_2$ capture measures in any power plant, so the proportionality of emission variation with CC variation was higher (similar to the coal-fired power plant share in the sector).

*Most probable range of variation of the key factors.* The most probable range of variation was defined for each key factor. Three main conditions were taken into account to set the

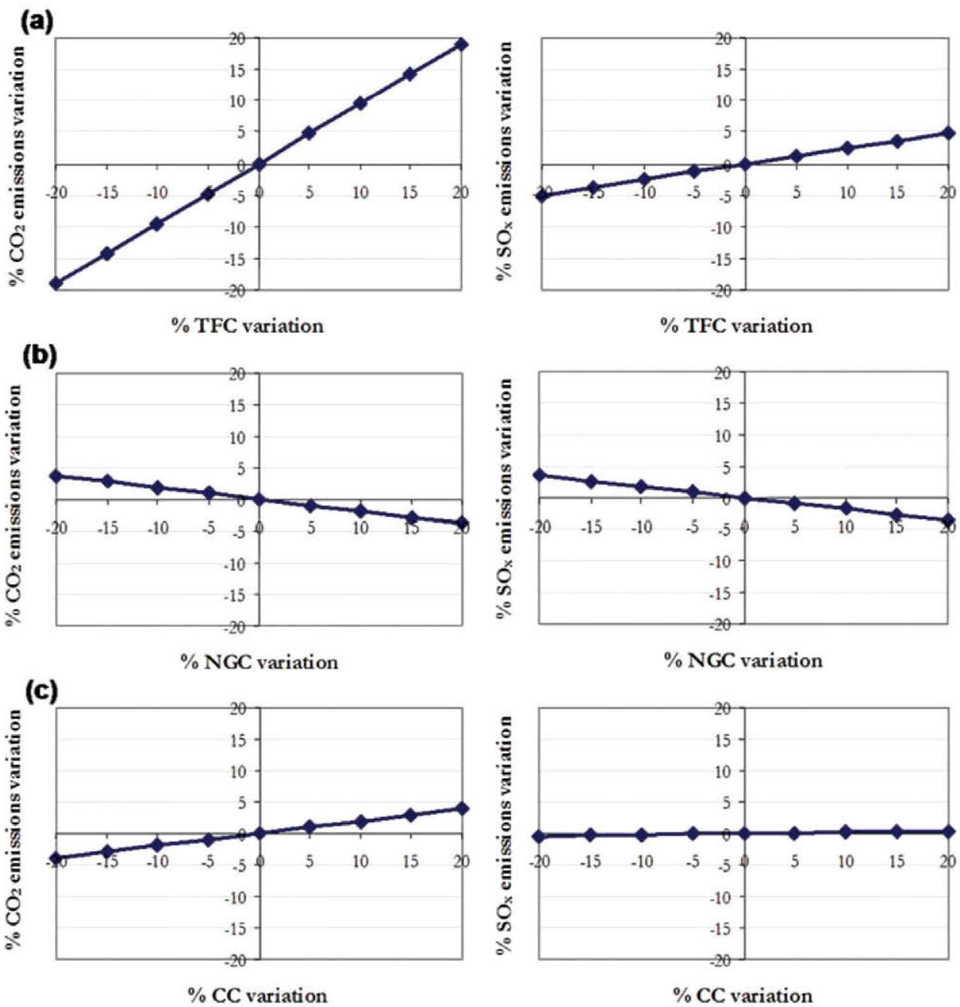


**Figure 1.** Effect of variation of key factors over power plants sector emissions: (a) total fuel consumption, TFC; (b) natural gas consumption, NGC; (c) coal consumption, CC.

ranges: (i) the energy planning provided by the General Directorate for Energy Planning (SGPE) of the Ministry of Industry, Tourism, and Trade (MITYC), (ii) information provided by the experts of MITYC, and (iii) the limits set by the NERP-LCP. The resulting ranges are shown in Table 2.

As shown in Table 2, the variation range defined for NGC was nonsymmetrical. According to the information provided by experts from MITYC in Spain, the penetration of natural gas was higher due to the number of combined-cycle power plant projects that were applied in Spain. That was the main reason for the +7% upper range variation. For the lower limit, a lower penetration of natural gas was unlikely according to the information provided by those experts, so it was consequently set to –2%.

Applying all the possible ranges, which correspond in this case to the variation on the three key factors (total fuel consumption, natural gas consumption, and coal consumption), the lowest emissions were produced by –5% TFC, +7% NGC, and –5% CC evolutions. On the other hand, the highest emissions were associated with a +5% TFC, –2% NGC, and +5% CC scenario.

*Effect on national total emissions.* The effect of the most probable range of variation of key factors over the total national emissions is represented in Figure 2a. The highest range of

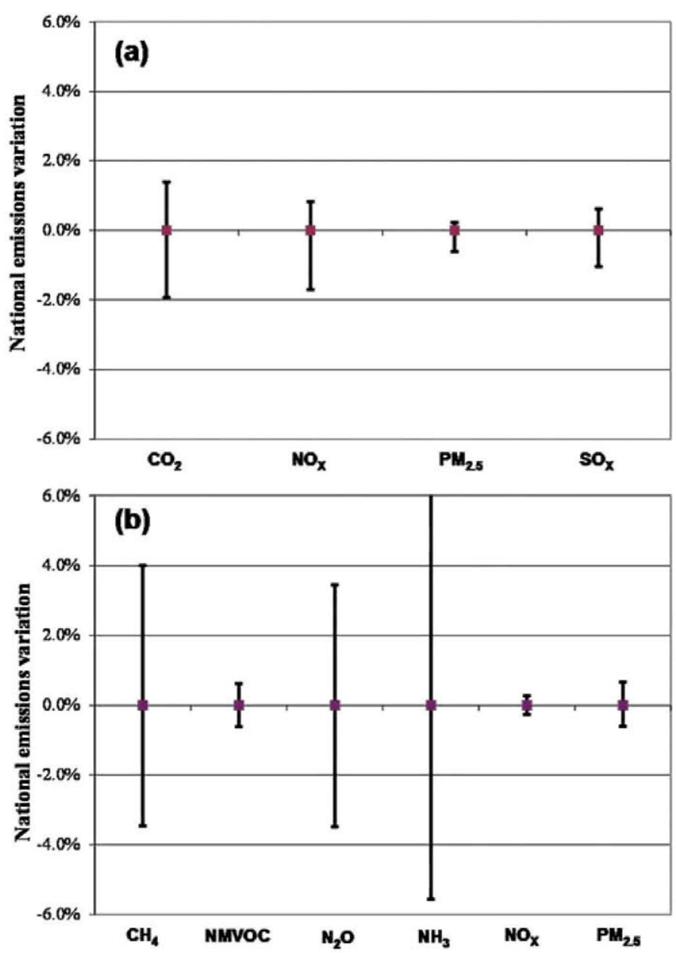


**Figure 2.** Range of variation of $CO_2$, $CH_4$, NMVOC, $N_2O$, $NH_3$, $NO_x$, $PM_{2.5}$, and $SO_x$ national emissions produced by UFSA over different sectors: (a) power plants; (b) agriculture and livestock.

variation was found for $CO_2$ emissions, ranging from +1.4% in the "high emission" case to –1.9% in the "low emission" case. The smallest deviation was found for $PM_{2.5}$, ranging from +0.2% to –0.6%. Although the power plants sector was the most important as far as $SO_x$ emissions are concerned (71% of the total national emissions in 2006), the UFSA analysis demonstrated that when changes in this sector were produced, the most affected pollutant was $CO_2$ as a result of the legislation restrictions (NERP-LCP). These bands increase as they move away from 2006, since this is the last year with emission data inventoried.

## Agriculture and livestock sector

This sector includes activities belonging to different SNAP groups: fertilizers production (SNAP 04.04), mobile motors and machines used in agriculture (SNAP 08.06), and agriculture (SNAP 10). This is a relevant sector for $CH_4$, $N_2O$, $NH_3$, and particulate matter emissions (Table 1).

*Key factors.* The modified parameters in this sector were:

- Field of cultures with fertilizers (FF).
- Inorganic fertilizer applied (IF).
- Number of livestock heads (NLH), specifically, the livestock types responsible for the highest emissions of $CH_4$, $N_2O$, $NH_3$, and particulate matter in Spain, that is, dairy cows, other cattle (OC), swine (fattening pigs [FP] and sows), sheep, and laying hens.
- Urea proportion of inorganic fertilization (UP).

FF and IF parameters were chosen for their contribution to national emissions (especially $NH_3$ and $N_2O$) and due to their relationship. Regarding livestock, the selected types produced important $CH_4$, $NH_3$, and PM emissions during manure management and via enteric fermentation. Finally, the proportion of urea in inorganic fertilization was chosen because of the high $NH_3$ emission factor in comparison with other kinds of N-fertilizers.

*Influence of key factors on sector emissions.* Figure 3 shows the effect of the key factors variation over emissions for some pollutants. In order to simplify the exposition, the effects of dairy cows, sows, sheep, and laying hens on emissions are not shown because their behaviors were similar than those of OC and FP, while their influence over emissions was less relevant.

Regarding FF, the effect over $CH_4$ emissions was almost negligible (Figure 3a). The increase in FF had only a slight response in the $CH_4$ emissions associated to rice yield. Figure 3a also shows that NMVOC emissions increased nearly proportionally to FF (although not presented, $NO_x$ and $PM_{2.5}$ emissions evolved similarly). However, no changes in $NH_3$ emissions were detected because when FF was modified, IF and fertilizers production were kept constant according to the information provided by the National Fertilizers Producers Association (ANFEE) for the WM scenario. As far as IF was concerned (Figure 3b), there was no effect on $CH_4$ emissions,

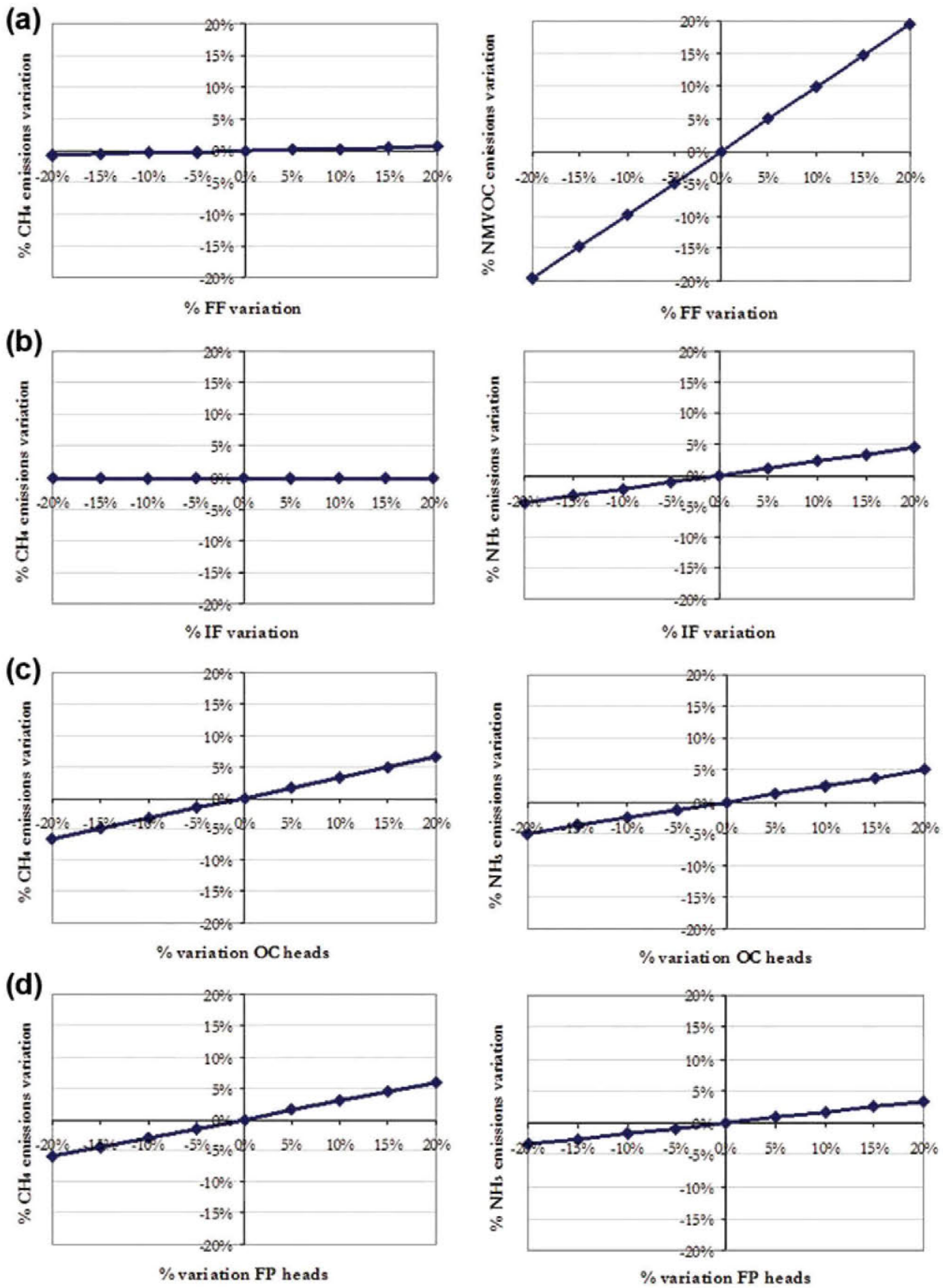


**Figure 3.** Effect of variation of key factors over agriculture and livestock sector emissions: (a) field of cultures with fertilizers, FF; (b) inorganic fertilizer applied, IF; (c) heads of other cattle, OC; (d) heads of fattening pigs, FP.

but when IF increased, $NH_3$ and, especially, $N_2O$ emissions rose (the latter not shown). This different response is because $N_2O$ emissions were mainly produced by crops while $NH_3$ emissions also depended on the manure management.

The effect of NLH over the emissions is shown in Figure 3c and Figure 3d. It mainly influenced $CH_4$ emissions (associated to enteric fermentation and manure management), $NH_3$ and $N_2O$ emissions (affected to a greater or lesser extent by organic nitrogen applied to crops and manure management), and PM produced during manure management operations. OC and FP were the most influential types of livestock because they had the highest emissions. Regarding laying hens, only a slightly influence on particulate matter emissions was found.

The effect of UP over the emissions was almost negligible. Although the $NH_3$ emission factor of urea was higher than those of other N-fertilizers, this fertilizer represented the 25% of the total inorganic nitrogen applied to crops.

*Most probable range of variation of the key factors.* Table 2 shows the most probable ranges of variations defined for each key factor. Both the FF and the IF used in the WM scenario were provided by experts from the Ministry of Environment, Rural and Marine Affairs (MARM), and ANFEE. The crops field had not changed significantly in the last 16 years and it was not expected to do so in the near future, so the proposed range of variation was low (±2%). The amount of inorganic fertilizer applied to crops had been more variable (standard deviation around 12% in the 1990–2006 period), so a variation range of ±10% was applied. There had not been large interannual variations in number of livestock heads since 1990, so important deviations from data provided by MARM were not expected in the next years. Therefore, the most probable range of variation was ±5 except for dairy cows and fattening pigs (with ±10%, because interannual variations were higher than 5% and/or standard deviation around 10%). However, according to data provided by experts from MARM, the upper and the lower limits were reduced to 5% for dairy cows and FP heads, respectively.

Although low emission potential fertilizers are expected to be more used in the future, in recent years the rate of utilization of urea was fairly constant, so the range of variation was set at ±5%.

*Effect on national total emissions.* The effect of the most probable range of variation of the key factors over the total national emissions is represented in Figure 2b. In the case of the agriculture and livestock sector, the upper emission band of uncertainty was determined by the addition of all the positive variation ranges presented in Table 2. On the contrary, the lower emission band was estimated by means of the negative ones.

The influence of the key factors of this sector over the national emissions was significant, especially for $NH_3$, $CH_4$, and $N_2O$. Concretely, the ranges of variation were from +6.1% to −5.6%, from +4.0% to −3.5%, and from +3.4% to −3.5%, respectively.

Regarding NMVOC emissions, even though the model was quite sensitive to FF (Figure 3a) the range of total national emissions variation was small (±0.6%). This is because crops fields were unlikely to deviate much from the projected values of the WM scenario and because this sector was not the most relevant in terms of emissions. With regard to $NO_x$ and $PM_{2.5}$ emissions, the importance of the key parameters was low (Figure 2b) because of the small significance of the agriculture and livestock sector comparing with the energy sector.

# Results and Discussion

## National results

The methodology previously explained was applied over the 12 highest emitting sectors regarding GHG and air pollutant emissions (Table 1). The uncertainty bands (upper and lower) were estimated by varying the driving factors of each sector and by calculating associated emissions. Therefore, results should be interpreted as bands of future emissions that would be produced assuming some sources of uncertainty as lack of quality of data, biases in model formulation, lack of scientific

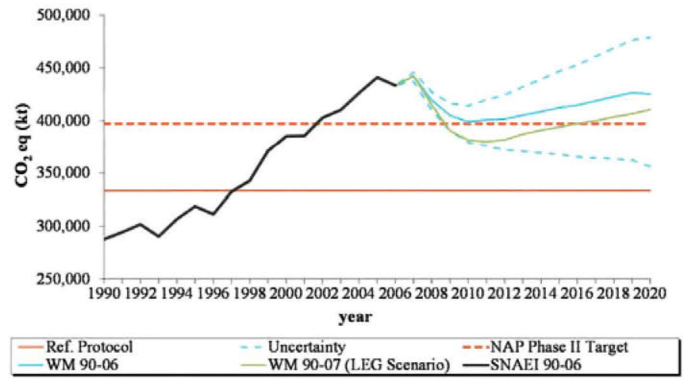


**Figure 4.** Uncertainty bands for $CO_2$ equivalent emissions: comparison with the LEG scenario and with the Kyoto Protocol (Ref. Protocol) and the National Allocation Plan (NAP Phase II Target) limits.

understanding, or the inability to predict future behavior (as mentioned in the Introduction section, obtaining qualitative results).

The total results obtained for the main pollutants are shown in Figure 4 and Figure 5. In addition to the outputs from WM90-06 scenario, the updated results from the reviewed version (WM90-07) are included in the graphs. The purpose is to understand whether recomputed emissions from a revised version of the scenario taking into account unexpected variability of activity rates fall within the uncertainty bands originally computed, thus giving some information on the robustness and the fitness for purpose of the methodology proposed.

Regarding $CO_2$ equivalent emissions (Figure 4), two different lines titled Reference Protocol and NAP Phase II Target were represented. The first one represented the maximum emissions for Spain in order to fulfill the Kyoto Protocol. However, as recognized in the Kyoto Protocol itself, countries had additional means of meeting their targets. These means were called flexibility mechanisms or Kyoto mechanisms. In accordance with the National Allocation Plan (NAP), NAP Phase II (Ministry of the Presidency [MP], 2006), Spain was allowed to emit 37% more emissions than those fixed by the Kyoto Protocol. This limit was represented by the line called NAP Phase II Target. According to this, Spain was close to complying with NAP in 2010 under the WM scenario.

Concerning NECD pollutants (Figure 5), results were more variable and only $SO_x$ (Figure 5b) complied with NECD, due to the emissions decrease associated with NERP-LCP restrictions and the reduction of sulfur content in petrol and diesel fuels, according to Directive 2003/17/EC (2003). The other pollutants were far above the legislation limits even considering the uncertainty bands. Recent official figures have confirmed this situation (MARM, 2012).

## Comparison between results from UFSA and low economic growth (LEG) scenario

Results from UFSA were compared with recomputed emission trends under LEG scenario. As it can be observed (Figure 4), although $CO_2$ equivalent emissions of the LEG scenario

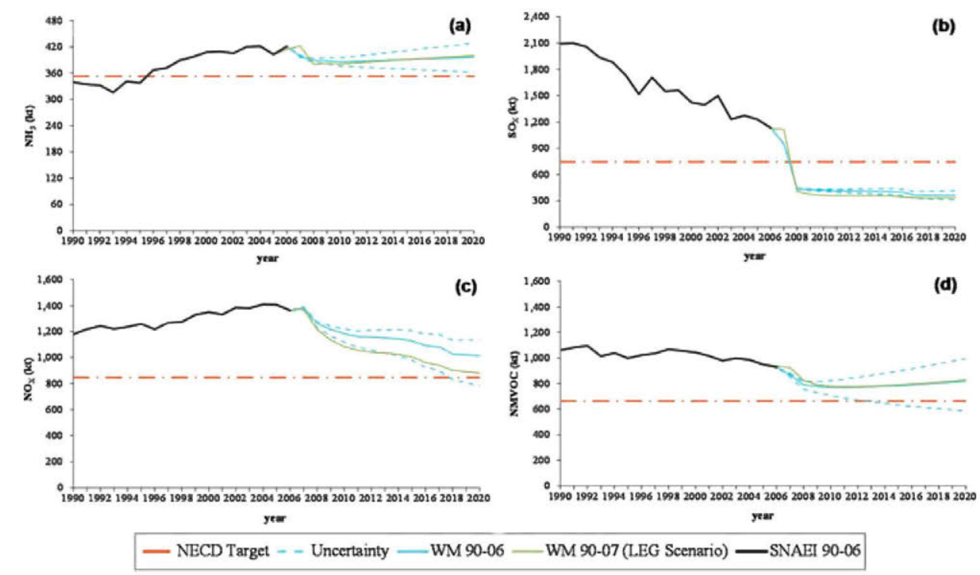

**Figure 5.** Uncertainty bands for NECD pollutants and comparison with LEG scenario for (a) $NH_3$ emissions, (b) $SO_x$ emissions, (c) $NO_x$ emissions, and (d) NMVOC emissions.

decreased sharply from 2007, the emission projections were within uncertainty bands. This situation was associated to the economic crisis, which caused a decrease in industrial activity and mobility, resulting in an energy consumption reduction (promoting a decrease in production). According to the results obtained for the LEG scenario, Spain clearly met the NAP limit.

Different findings were detected for air pollutants (Figure 5). In the case of $SO_x$ and $NO_x$ (Figure 5b and Figure 5c, respectively), the emissions decrease related to the economic crisis caused LEG scenario projections to evolve under the lower uncertainty band, until 2014 at least. Nevertheless, different results were obtained for $NH_3$ (Figure 5a) and NMVOC (Figure 5d), with LEG emission projections inside the uncertainty bands. On the other hand, except for $SO_x$, emissions of NECD pollutants did not fulfill legislation limits even in the LEG scenario. For this reason, an important effort was necessary to decrease emissions so as to meet NECD limits.

# Conclusion

A methodology to estimate nonstatistical qualitative uncertainty bands for emission projections using simplified sensitivity analysis (UFSA) were explained. The UFSA was applied to Spain for the 12 highest emitting sectors that were responsible for at least the 80% of the national emission of gaseous pollutants according to Spain's National Atmospheric Emission Inventory 1990–2006 (MARM, 2008). The methodology has been applied to the "with measures" (WM) scenario computed by means of the consistent emission projection (CEP) model for Spain. The most important findings of this work were:

- UFSA quantified the total uncertainty in a more simple way than traditional methods like ARIMA or nonparametric bootstrap methodologies.
- The evolution of national emission projections can be explained to a large extent by the analysis of a limited number of emitting sectors. At the same time, these sectors depend on a narrow number of key parameters.
- This methodology allowed one to identify/assess the main sources of uncertainty associated to emissions and emission projections.
- The application of UFSA for Spain's emission projections showed a very good performance. It was compared with official inventories and recomputed emission trends in a low economic growth perspective (LEG), and uncertainty bands were able to reflect most of unexpected variation on activity rates due to external conditions such as current economic crisis. Therefore, it appears as a good possibility to carry out uncertainty assessments for countries that are currently developing sensitivity analyses.
- Emissions of National Emission Ceilings Directive (NECD) pollutants exceeded legislation limits (even in the LEG scenario), except for SOx, and therefore additional efforts were necessary to meet NECD limits. However, regarding greenhouse gases emissions, the WM scenario was close to complying with the National Allocation Plan (NAP) in 2010 (but not during the 5-year commitment period, 2008–2012), whereas the LEG scenario clearly fulfilled NAP. Both scenarios evolved far above Kyoto Protocol target for Spain and within uncertainty bands.

As a consequence, UFSA could be used for other countries or regions to obtain uncertainty bands for emission projections in a simple way, helping the policymaking progress with robust conclusions.

# Funding

This study was partially funded by the Spanish Ministry of Environment, Rural and Marine Affairs.

## Nomenclature

| | |
|---|---|
| ANFEE | National Fertilizers Producers Association |
| CC | Coal Consumption |
| CEP | Consistent Emission Projection Model |
| FF | Field of Cultures with Fertilizers |
| FP | Fattening Pigs |
| GDP | Gross Domestic Product |
| GHG | Greenhouse Gas |
| IF | Inorganic Fertilizer Applied |
| KP | Kyoto Protocol |
| LEG | Low Economic Growth Perspective Scenario |
| MARM | Ministry of Environment, Rural and Marine Affairs |
| MITYC | Ministry of Industry, Tourism and Trade |
| NAP | National Allocation Plan |
| NECD | National Emission Ceilings Directive |
| NERP-LCP | National Emission Reduction Plan for Large Combustion Plants |
| NGC | Natural Gas Consumption |
| NMVOC | Non-Methane Volatile Organic Compounds |
| NLH | Number of Livestock Heads |
| OC | Other Cattle |
| SA | Sensitivity Analyses |
| SGPE | General Directorate for Energy Planning |
| SNAEI | Spain's National Atmospheric Emission Inventory |
| TFC | Total Fuel Consumption |
| UFSA | Uncertainty from Sensitivity Analysis Method |
| UP | Urea Proportion of Inorganic Fertilization |
| USA | United States of America |
| WM | With Measures Scenario |


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